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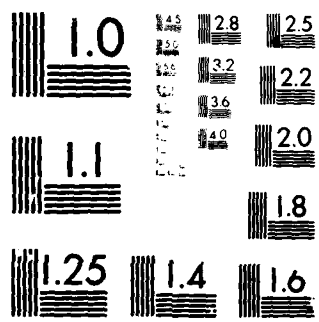

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ROCKET PLUME BURN HAZARD

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3 JANUARY 1980

FINAL REPORT
AIRTASK NO. WF 51-523-000
Program Element No. 62758N

Prepared for
NAVAL AIR SYSTEMS COMMAND
Department of the Navy
Washington, D. C. 20361

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER
14) NADC-80008-60

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
6) Rocket Plume Burn Hazard

5. TYPE OF REPORT & PERIOD COVERED
9) Final Repts

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
10) A.M. Stoll, J.R. Piergallini [redacted] M.A. Chianta

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Aircraft and Crew Systems Directorate
Naval Air Development Center
Warminster, Pa. 18974

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Airtask No. WF 51-523-000
Work Unit No. 62758N

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Air Systems Command
Department of the Navy
Washington, D. C. 20361

12. REPORT DATE
11) 3 Jan [redacted] 80

13. NUMBER OF PAGES
18

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
16) F51523

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17) WF51523011

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Rocket plume burn hazard
Multiple ejection burn hazard
Short-term flame exposure burns

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

By use of miniature rocket engines, the burn hazard posed by exposure to ejection seat rocket plume flames was determined in the anaesthetized rat. A reference chart is provided for predicting equivalent effects in human skin based on extrapolation of earlier direct measurements of heat input for rat and human burns. The chart is intended to be used in conjunction with thermocouple temperature measurements of the plume environment for design and modification of escape seat systems to avoid thermal injury on ejection from multiplace aircraft.

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

With the advent of multiple-place aircraft ejections a new burn hazard to the aircrew was introduced. This hazard is created by flames generated on firing of ejection seat rockets such that the second and subsequent ejectees are exposed to the flames of those preceding them in sequential ejections while in simultaneous ejections the seat trajectories may be such that similar exposures also occur.

PURPOSE AND APPROACH

The present study was undertaken to determine the maximum heat flux-exposure time and flame temperature permissible for contact with bare skin without causing serious burn injury.

Although suitable data exist on heat transfer by radiation (7), clean flame (8), and conduction (9) contacts, none were available for the "dirty" flame of the rocket plume which presents a mixture of the three modes of transfer. It was necessary therefore, to provide a heat source that would simulate the rocket plume not only in level of heat flux but also in luminosity, radiation and particulate matter content. The plan was then to expose anaesthetized, depilated white rats to the heat source at various levels of energy until the heat flux-time exposure resulted in minimal white burn, equivalent to a first degree (non-blistering) burn in the human. At this level the flame temperature would be measured to establish the criterion for permissible flame contact as measured at the operational site of exposure.

EXPERIMENTAL PROCEDURES AND MATERIALS

A synthesis of the data from available sources (4 and 1) indicated that the maximum temperature of the rocket plume is about 2760°C. However, this temperature was postulated from extrapolations of actual measurements (1) and computer analyses of combustion ingredients (W. Stone, NWL, China Lake, personal communication, Jan 1977), neither of which methods provides information on the

gradient within the flame envelope. Consideration of the possible sources of flames at this temperature indicated that acetylene-oxygen, about 15.5% combustible, would produce a flame of 2760°C (2). However, this flame is very clean and short in length, therefore technically unsatisfactory. Other sources were considered and rejected for similar reasons. Finally, the most appropriate source was determined to be a miniature rocket engine which uses combustion ingredients similar to those in the ejection seat rocket and produces a similar "dirty" flame.

Suitable rocket engines were procured.* Trials with several engine types resulted in selection of the B40P. This type is supplied without a smoke-trailer and fires with no delay between burnout and ejection charge activation so that an approximately square-wave pulse is produced. The energy rises precipitously to a maximum at 0.3 to 0.4 sec after ignition, maintaining a high level to 1.0 or 1.1 sec, dropping abruptly to zero (Fig 1). The upper curve traces the heat pulse observed radiometrically while the lower trace is that of a monitor thermocouple exposed to the same pulse. Measurement of the energy intensity proved to be a difficult task due to the deposition of black or gray gunk on the face of any instrument placed in the path of the flames. However, it was possible to trace the pulse shape by sidewise radiometric observation and to measure the total heat transfer by means of a specially-constructed copper tab calorimeter calibrated by reference to standard laboratory heat sources (3).

To define the hazardous environment, apparatus was set up for exposing experimental animals at various intensities of heat input. This apparatus (Fig 2) consisted of a vise to hold the rocket engine, an ignition source, a track on which was mounted a transite shield 11-3/4 in. (29.8 cm) X 20-3/4 in. (52.7 cm), 0.178 in. (4.5 mm) thick, having a circular aperture 3/4 in. (19 mm) in

* Ester Industries, Penrose, Colorado

diameter, with a platform and mesh restraint affixed to the back for holding the animal during exposure. A yardstick positioned beside the track facilitated adjustment of the distance from the face of the rocket engine to the skin surface of the animal for exposure at various flux intensities. A chromel-alumel thermocouple was epoxied to the front face of the shield at the edge of the exposure aperture to monitor the heat pulse during animal and calorimeter exposures so that variations due to differences in the rocket engines themselves (e.g., heat output, centering of the blast with respect to the target, etc.) would be flagged. Outputs from the monitoring thermocouple were recorded on suitable equipment (3).

Routinely, a Wistar male rat, approximately 400 gm in weight, was anaesthetized with sodium pentabarbitol, 45 mg/kg, I.P., and depilated on both sides by clipping and application of Nair depilatory. Twenty-four hours later the rat was again anaesthetized, the exposure site masked with three layers of 3M Micropore Surgical Tape having a 3/4 in. (19 mm) hole which was aligned with the shield aperture during mounting of the animal on the exposure platform, and subjected to a rocket engine firing at the selected distance. A second exposure was made in the same manner on the other side of the rat and the energy level measured in a third firing using the copper calorimeter. Immediately after each rat exposure the black-gray deposit was removed from the skin by gentle washing with tepid water and soap. Thereupon, the burn effect was assessed visually and followed subsequently until healing was complete. Masking with tape applied directly to the skin is essential to limiting the burn to the aperture area as the blast invariably pushes the skin back from the transite shield and admits flames to the area surrounding the selected skin site. A white burn about 1 cm in diameter within the exposed area, similar to that described earlier in establishing equivalency with the human threshold blister (7), was the criterion applied. Although it would be desirable to measure

tolerance time vs energy throughout a range of exposure times, this method could not be used because of the necessity of using rocket engines to produce the mixed-mode heat transfer appropriate to the purpose. Therefore, the desired end point was bracketed by more severe and less severe injury inflicted in a fixed exposure time at various flux intensities.

Exposures were made at six distances from the rocket engine face, i.e., 9 in. (22.9 cm), 12 in. (30.5 cm), 14 in. (35.6 cm), 16 in. (40.6 cm), 18 in. (45.7 cm) and 19 in. (48.3 cm). In all, 34 animal exposures were made with calorimeter measurements of heat flux after each set of two exposures. Following completion of the entire series another set of measurements was made with the calorimeter to confirm the flux determinations during the animal exposures and to correlate these flux intensities with the monitor thermocouple indications and with flame temperature measurements as indicated by a copper-constantan thermocouple on the front surface of the shield across the exposure aperture. For the latter measurement #30 gauge wire was used to minimize flame temperature measurement error due to thickness of the wire and yet remain intact when subjected to the rocket blast. At this thickness (thermojunction = 0.509 mm) the error would be expected to be <-2% when permitted to come to thermal equilibrium in the flame (10). However, due to the shortness of this pulse it is certain that the flame temperature indicated is appreciably lower than actual. Similar measurements with the same thermocouple at 1 sec in a propane gas flame at 1200°C yielded readings of 649°C, or 54% of the true temperature. Whether the same ratio pertains in the rocket flame measurement is problematic given the differences in characteristics of these two sources. Nevertheless, the indications are reproducible and therefore may be used for correlations with measured values of thermal flux.

RESULTS

At the beginning of the animal exposures a few intradermal thermocouple

measurements of skin temperature rise were made by insertion of a #40 gauge copper-constantan thermocouple in the exposure site. The skin temperature rise followed the rocket pulse shape (Fig 1) as seen in Fig 3, a record from a 9 in. (22.9 cm) exposure. The delayed return to initial temperature may be attributed, partially at least, to the heavy deposit of black material on the skin at this distance. The temperature rises observed were 137.1°C at 0.4 sec, 120.2°C at 0.7 sec and 100.9°C at 1 sec. The effect was very severe burning of the skin which became stiff and leathery, formed a very thick and extensive scab and eventually healed with residual scarring.

The results in terms of burn severity variation with distance from the rocket engine face, heat flux and indicated flame temperature are summarized in Fig 4. It is seen that as the distance increased the flux intensity, flame temperature and resultant burn severity decreased commensurately. The standard white burn effect, (i.e., a white burn approximately 1 cm in diameter which produces a light scab within 24 hours) was achieved at a distance of 16 in. (40.6 cm) at a heat input of 1.84 cal/cm^2 sec and a flame temperature indication of 208°C (406°F). More severe burns occurred at higher inputs and less severe at lower inputs with borderline effects, roughly equivalent to first degree burns, at the 19 in. (48.3 cm) distance. The total pulse in all instances lasted 1.0 to 1.1 sec with significant heat input prevailing for 0.6 to 0.7 sec. At the shorter distances (higher heat flux) black deposits occurred on the skin and were removed by gentle washing with soap and tepid water. Lighter deposits occurred at the 14 in. (35.6 cm) position giving way to progressively lighter gray deposits with numerous petechiae visible at the 16 in. (40.6 cm) and longer distances.

DISCUSSION

This series of experiments was designed to provide a practical means of determining the burn hazard posed by multiple ejection seat rocket plumes both

in the aircraft and in the air. The information desired by the seat design engineer (5) was the degree-second parameter at the skin surface to produce first, second and third degree burns. Unfortunately, because of the unique quality of the flame it was not readily possible to duplicate the flame and to vary the exposure time simultaneously as could have been done with a continuous, pure flame. It is possible, by reference to earlier work, to approximate the values desired. White burn data compiled by both NML and NADC (7) produced experimental data on absorbed energy rates and tolerance time to the white burn end point. These data were extrapolated to shorter times as shown in Fig 5 and the standard white burn energy rate in the present study (i.e., 1.8 cal/cm^2 sec measured at the 16 in. position) was located on this line. This point occurs at about 0.6 sec tolerance time which is, in fact, the time for which the maximum energy was absorbed. Although the total pulse exposure time was 1.0 sec, it was not a true square wave and the maximum level varied from beginning to end by about +14% to -14% of the mean. The calorimeter value is the square wave equivalent of the total pulse, therefore, the maximum and minimum peaks were actually 2.1 and 1.6 cal/cm^2 sec, respectively. Again referring to Fig 5, at 1.6 cal/cm^2 sec tolerance time would be 0.66 sec and at 2.1 cal/cm^2 sec, 0.46 sec if each level were a square-wave. It is well known that the law of reciprocity does not hold over a long range (6) but within the short range of time concerned here it is likely that the error incurred by assuming the mean (1.8 cal/cm^2 sec) to be the square wave level is acceptably small.

Building upon this assumption, the equivalent square-wave energy measured calorimetrically and simultaneous flame temperature indications from the #30 gauge copper-constantan thermocouple, are plotted in Fig 6 in log-log coordinates. These data are then used in conjunction with Fig 5 to provide the degree-second values desired, shown in Fig 7. Figure 7 is constructed simply by 1) finding the equivalent flux for a given indicated flame temperature in Fig

6; 2) finding the tolerance time corresponding to this flux in Fig 5; and 3) plotting this tolerance time against the original indicated flame temperature. The resultant line is the degree-second parameter for white burn in the rat, corresponding to a minimal blister (borderline 1st-2nd degree burn) in the human. Points to the left of this line would imply little or no injury and points to the right, greater than minimal blistering and worse i.e., severe 2nd degree, 3rd degree, char, etc.

In applying this information, caution must be exercised to assure that the indicated flame temperatures are equivalent to those used here. Different measurement systems will yield different temperature indications. For example, finer thermocouple wires, if they do not disintegrate, may be expected to respond faster and indicate higher temperatures; coarser thermocouple wires, lower temperatures; thermistors, depending upon construction, size and conditions of use may yield either higher or lower temperature indications. For safety, the proposed measuring system should be related to the present system by direct one-second measurements of output from a #30 gauge copper-constantan thermocouple and from the proposed sensor in a flame at known heat flux levels. From such measurements the abscissa in Fig 6 may be adjusted to reflect the equivalent flame temperatures indicated by the proposed system at given heat flux levels. The same coorections can then be applied to the abscissa in Fig 7 to provide a working chart. Judging from the discrepancy noted on exposure to the propane flame (-46%), these corrections could be very substantial.

CONCLUSION

The procedures and results described represent a practical system for estimating the burn hazard posed by exposure to rocket flames. A reference chart is provided for determining the severity of burn hazard from measurements of flame temperatures at impingement sites in the plume environment. Such measurements may be made at strategic locations within the cockpit and by telemetry

from the airborne ejection seats. These data may then be used in the design of seat systems to avoid thermal injury on multiple ejections.

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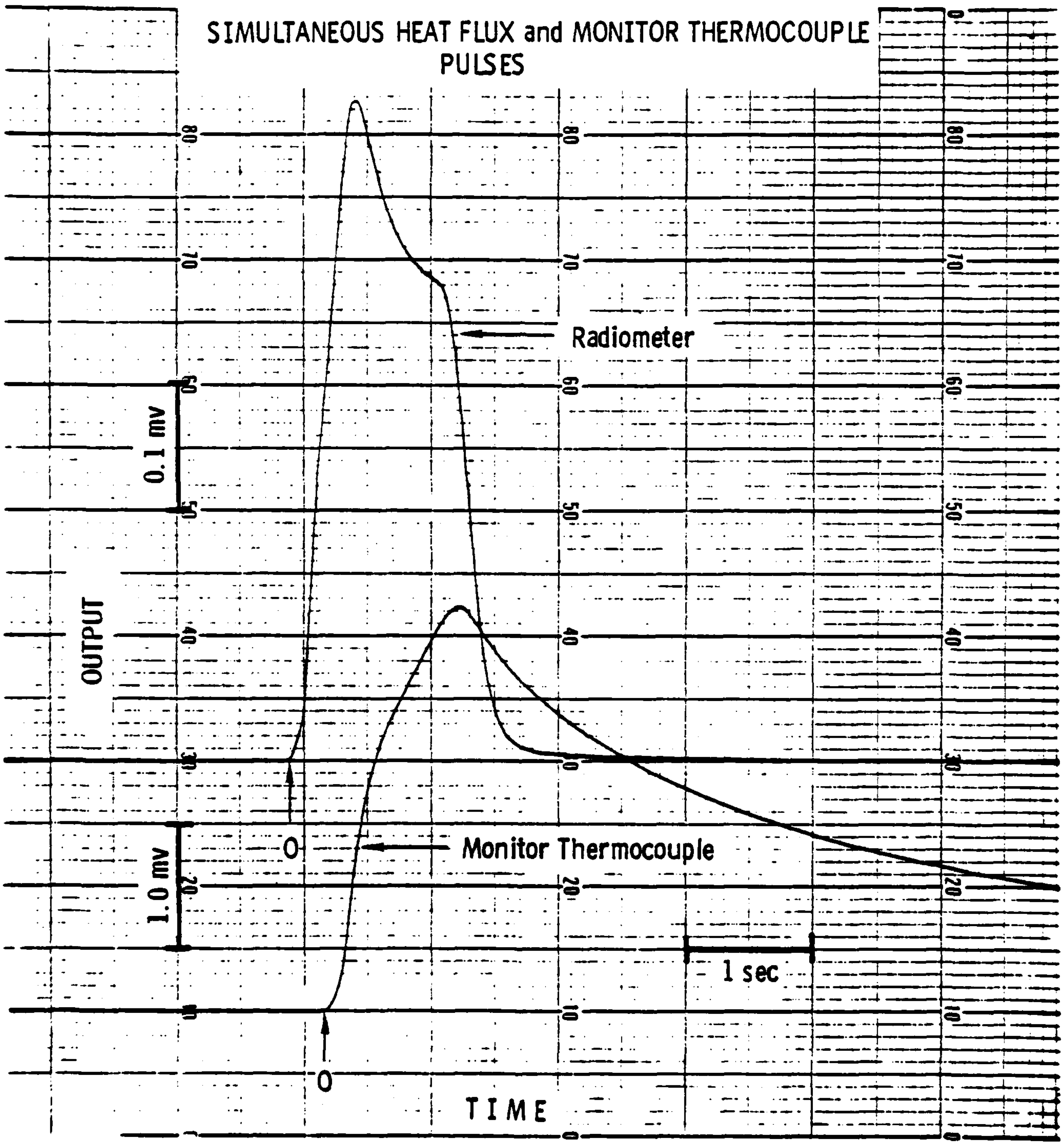

FIGURE 1 - Pulse shape of rocket engine discharge.

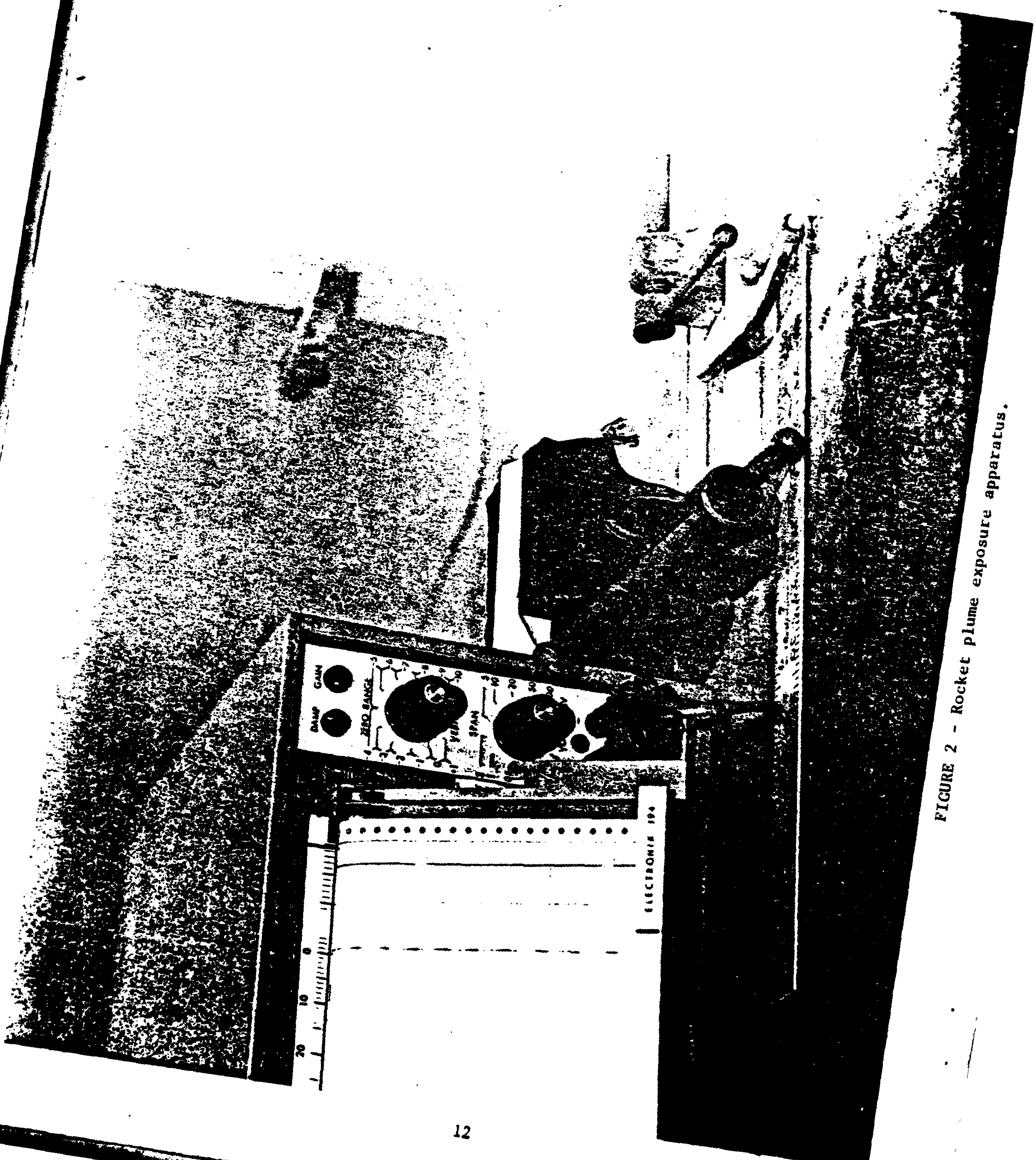

FIGURE 2 - Rocket plume exposure apparatus.

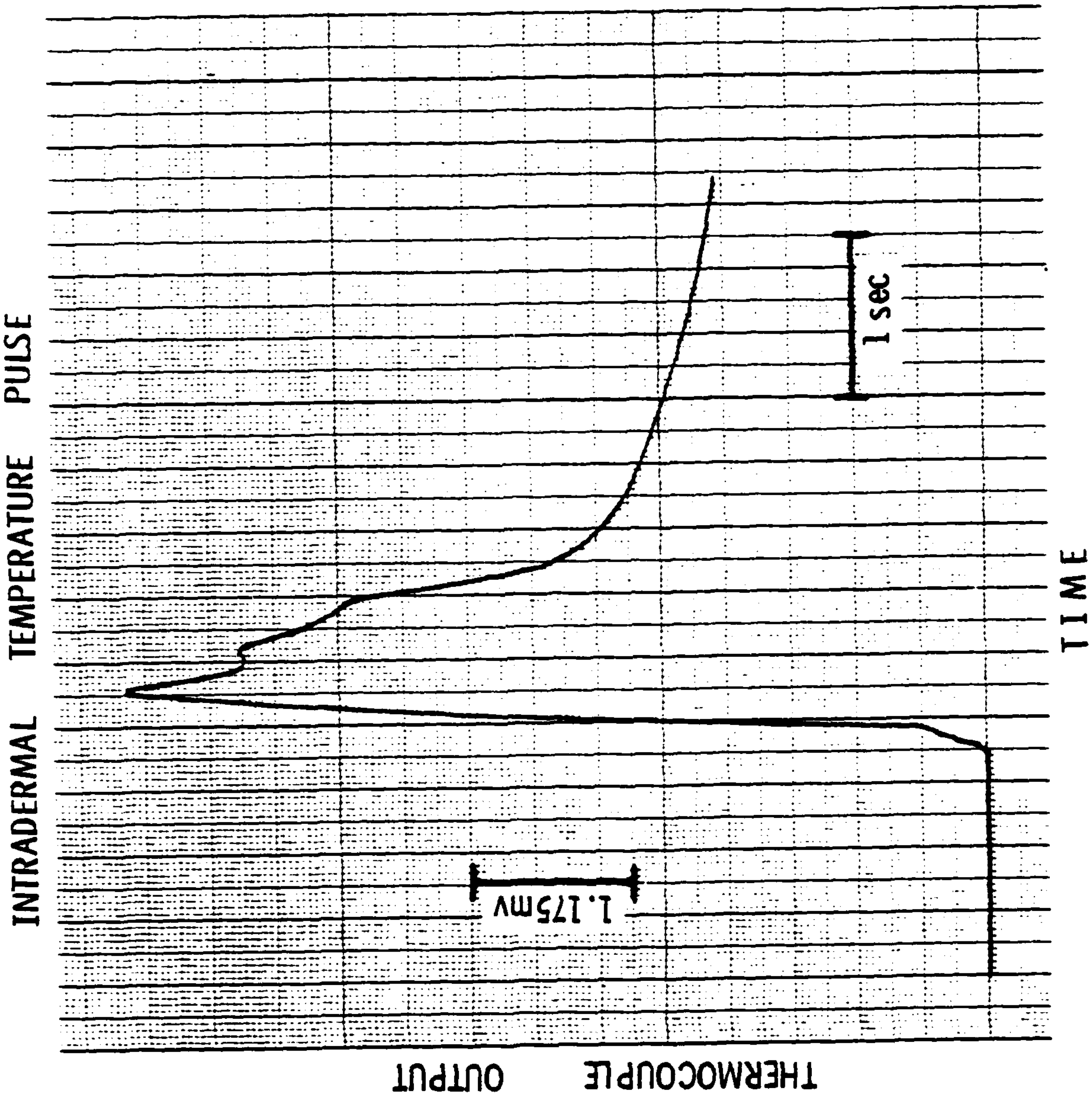

FIGURE 3 - Pulse shape of intradermal temperature rise during exposure.

THERMAL EFFECTS VARIATIONS WITH DISTANCE

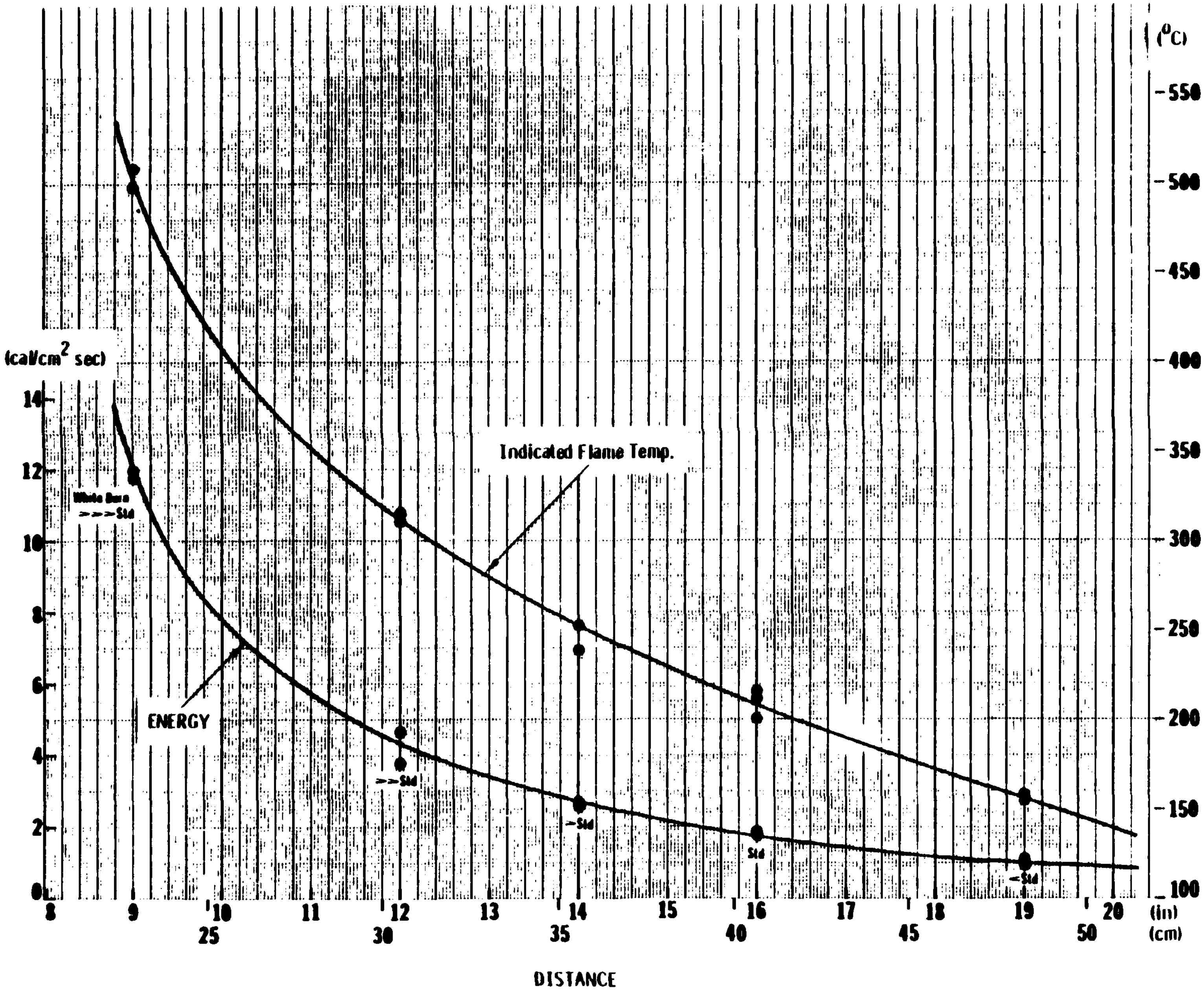

FIGURE 4 - Heat flux, and flame temperature as indicated by thermocouple at 1 sec related to distance from rocket engine and correlated with burn severity

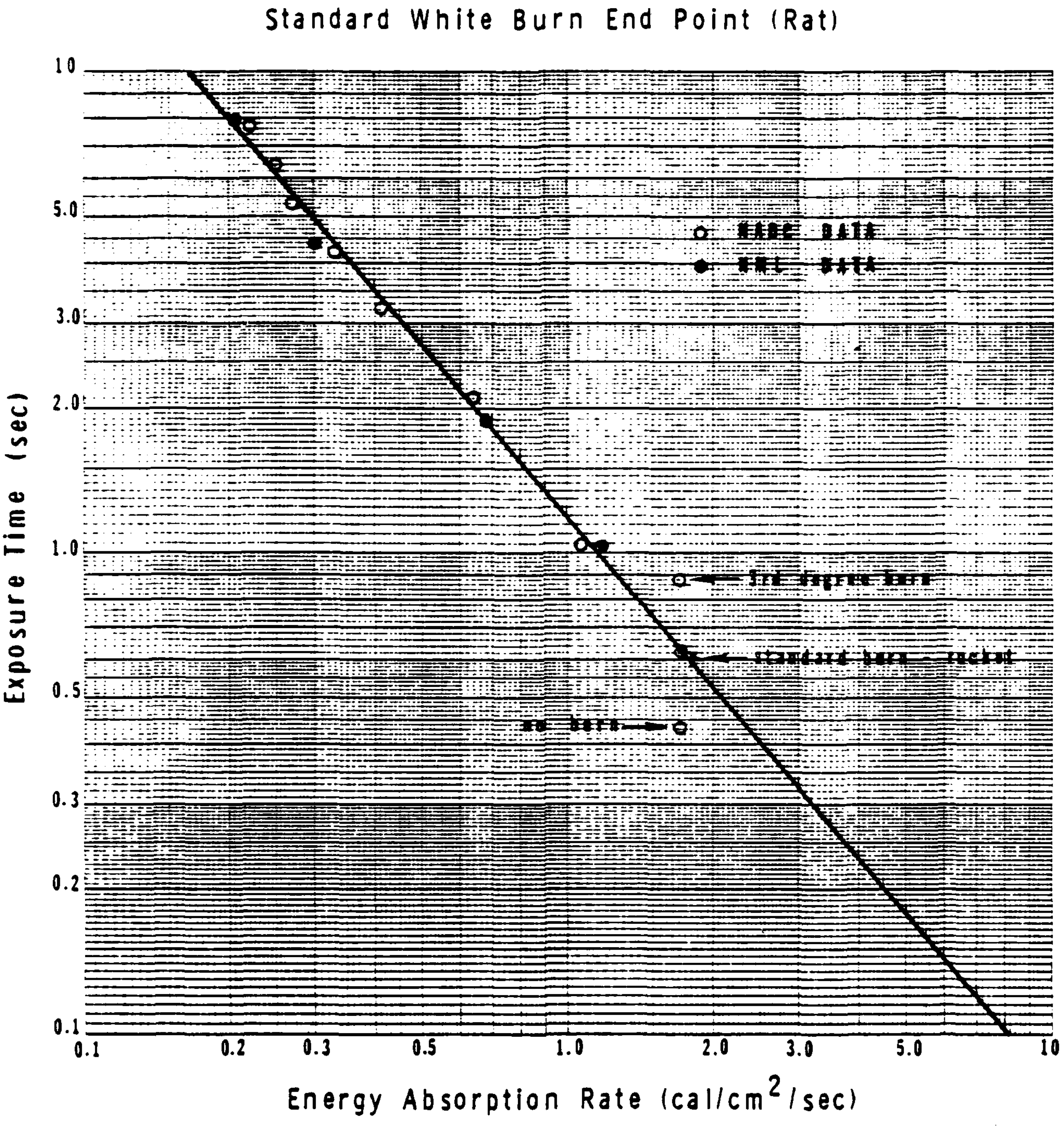

FIGURE 5 - White burn exposure time vs energy absorption rate extrapolated from Naval Material Laboratory (NML) and Naval Air Development Center (NADC) data.

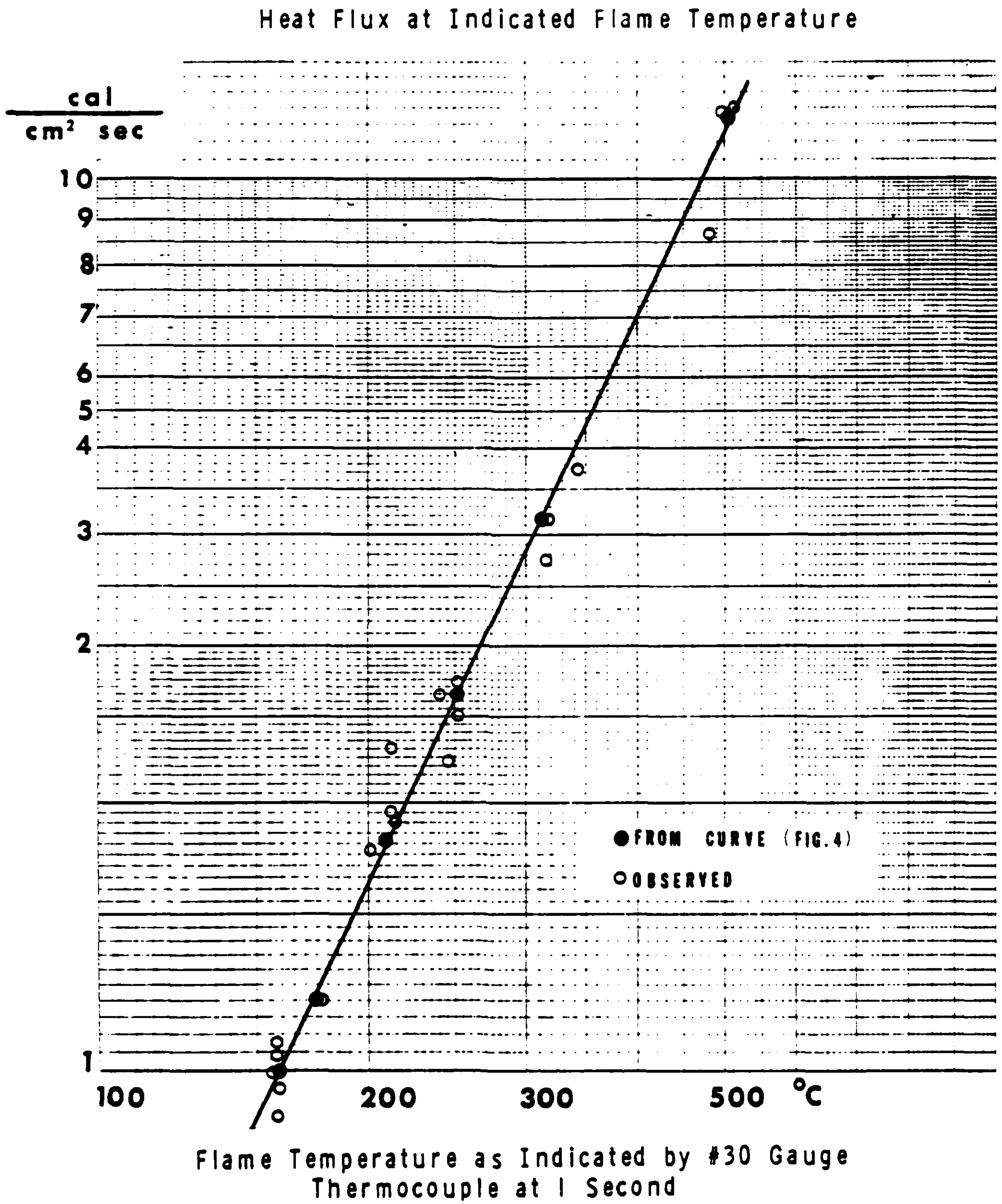

FIGURE 6 - Heat flux vs flame temperature as indicated by #30 gauge copper-constantan thermocouple at 1 sec.

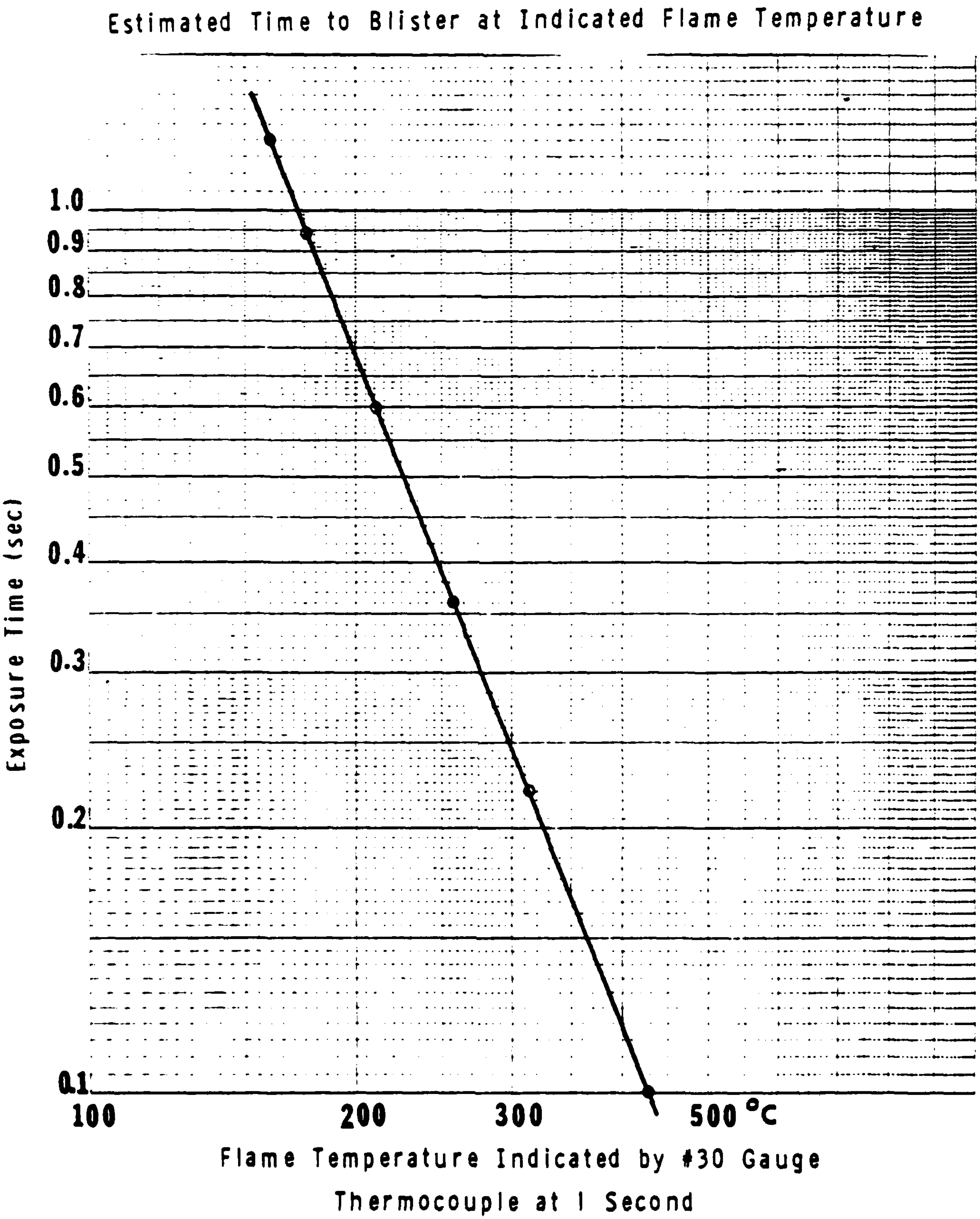

FIGURE 7 - Exposure time vs indicated (1 sec) flame temperature for minimal 2nd degree burn in human.

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